Large Scale Structure

Groups and Clusters

Reminder – Our Address

Levels of organization:

- Stellar Systems
- Stellar Clusters
- Galaxies
- Galaxy Groups and Clusters
- Galaxy Superclusters
- The Universe

Everyone should know where they live:

- The Solar System
- (we don’t live in a cluster)
- The Milky Way Galaxy
- The Local Group
- Laniakea Supercluster
- The Universe

Descriptions of Groups and Clusters

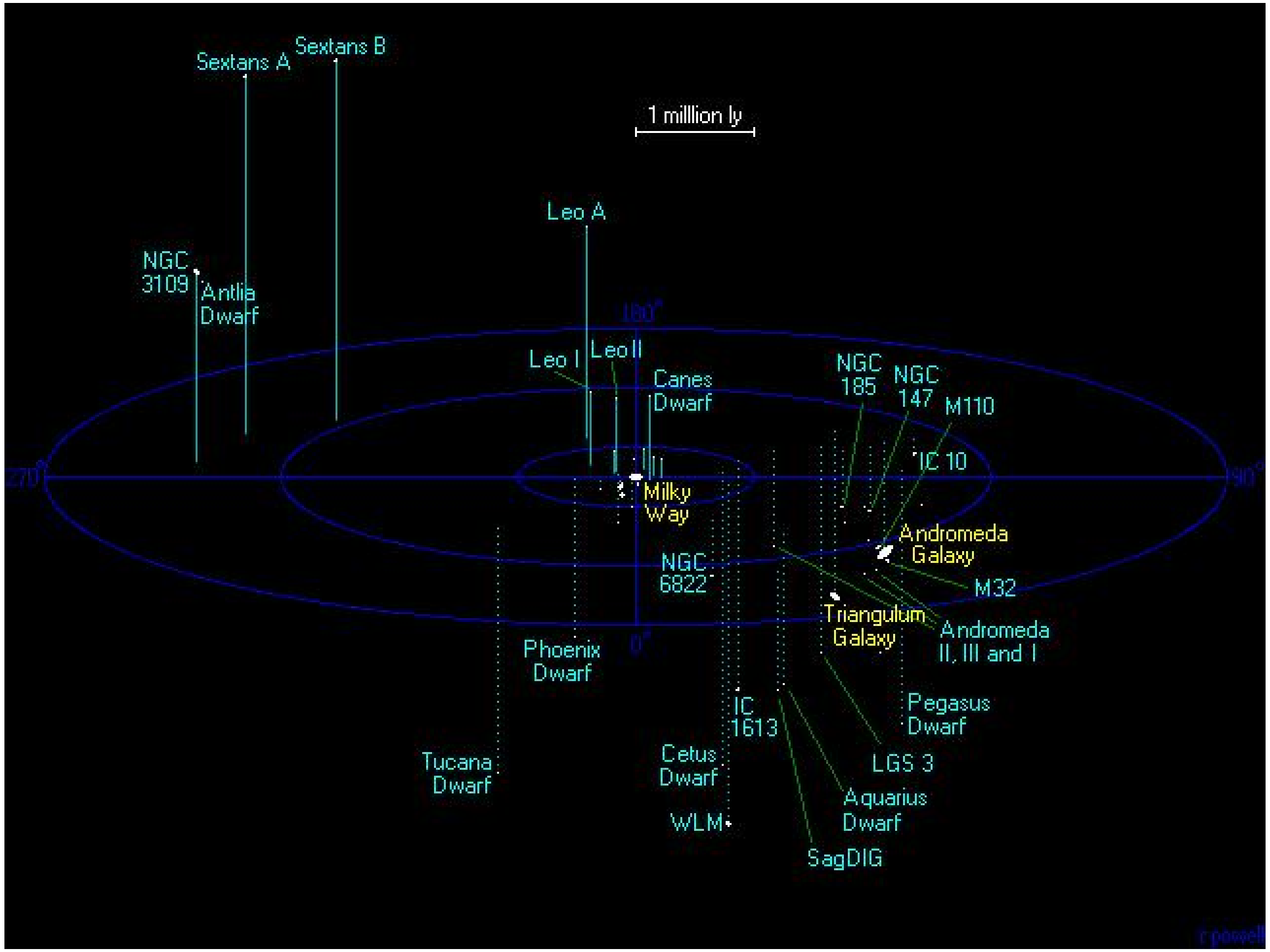
Galaxies are *not* distributed randomly through space

- Concentrated in collections called *Groups* and *Clusters*
- Groups and clusters range from about $10^{13}\ M_\odot$ – $10^{15}\ M_\odot$
- Range in size from 2 Mpc to 10 Mpc across
- They are categorized by how many bright galaxies they have
  - *Bright* is vague, but roughly brighter than 10% of the Milky Way
- The two types of collections are *groups* and *clusters*
  - Groups: < 50 bright galaxies, (about $10^{13}\ M_\odot$)
  - Clusters: ≥ 50 bright galaxies, (about $10^{14}\ M_\odot$ or $10^{15}\ M_\odot$)

Our Group – The Local Group

It has about 120 total galaxies

- Three spiral galaxies – two of them large
  - Milky Way Galaxy – a SBb or SBc or SBbc
  - Andromeda Galaxy (M31) – SAb
  - Triangulum galaxy (M33) – SAc or SAd

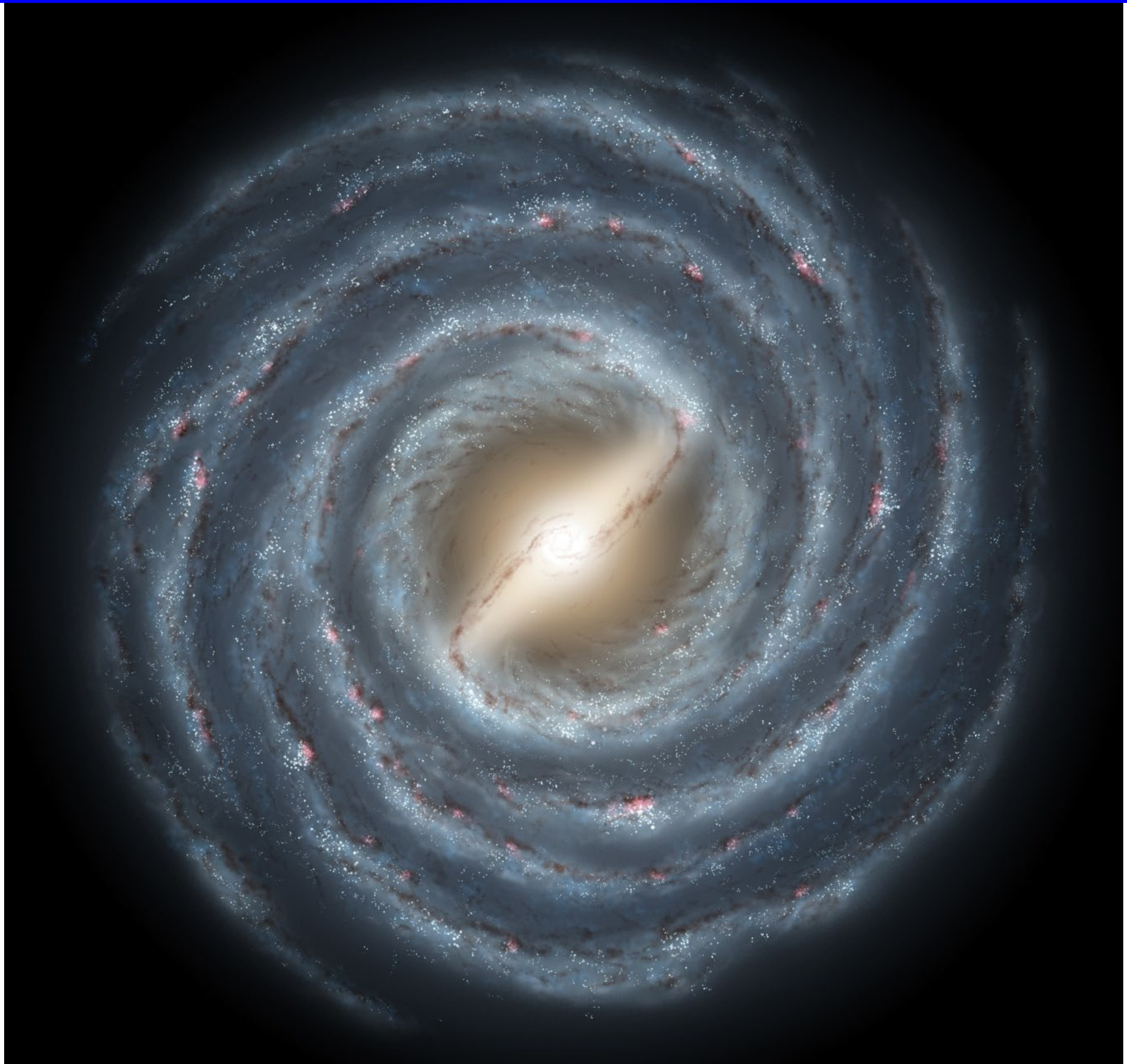


- Several small satellites of these galaxies

- Several miscellaneous galaxies

- Total diameter about 3 Mpc

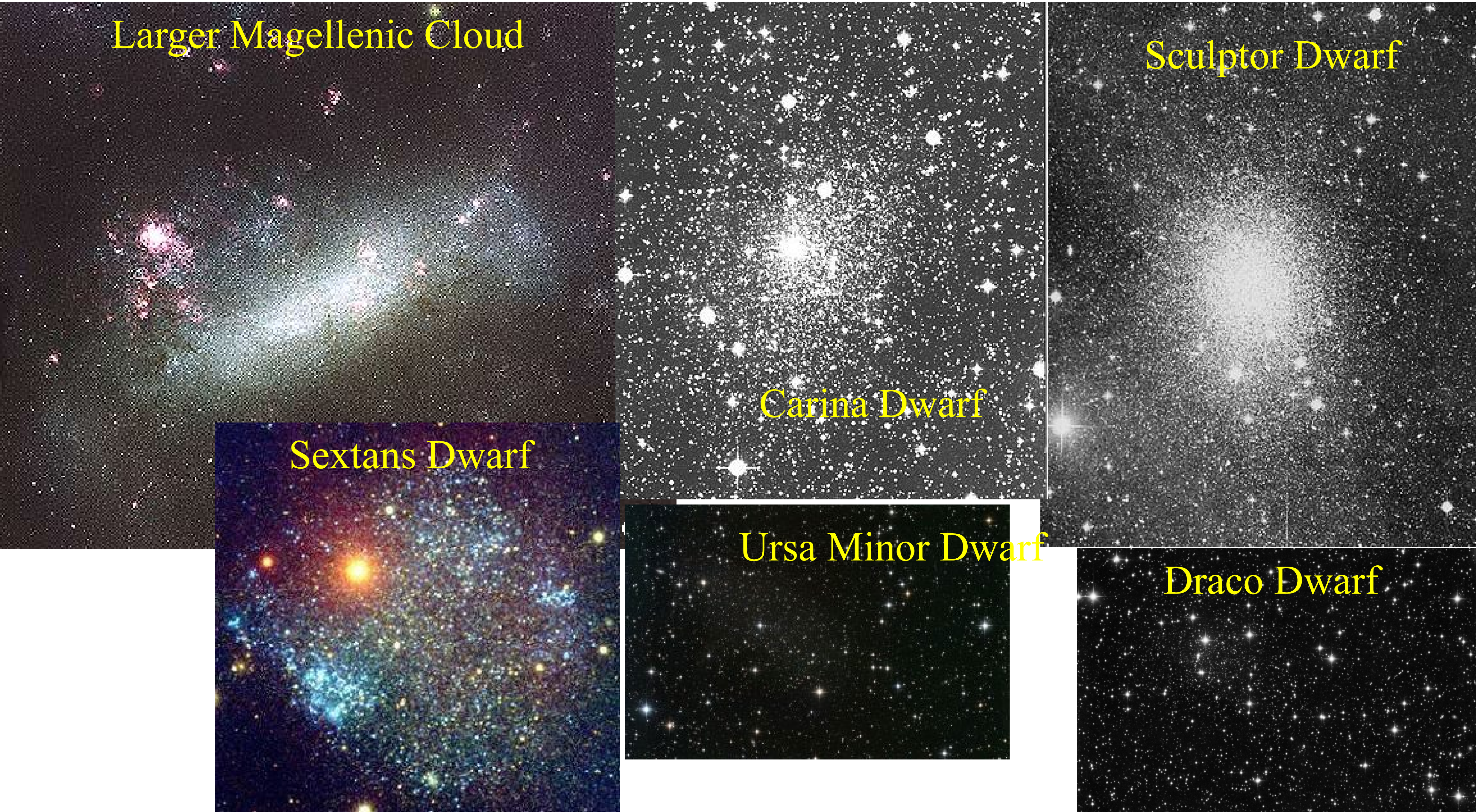
The Milky Way



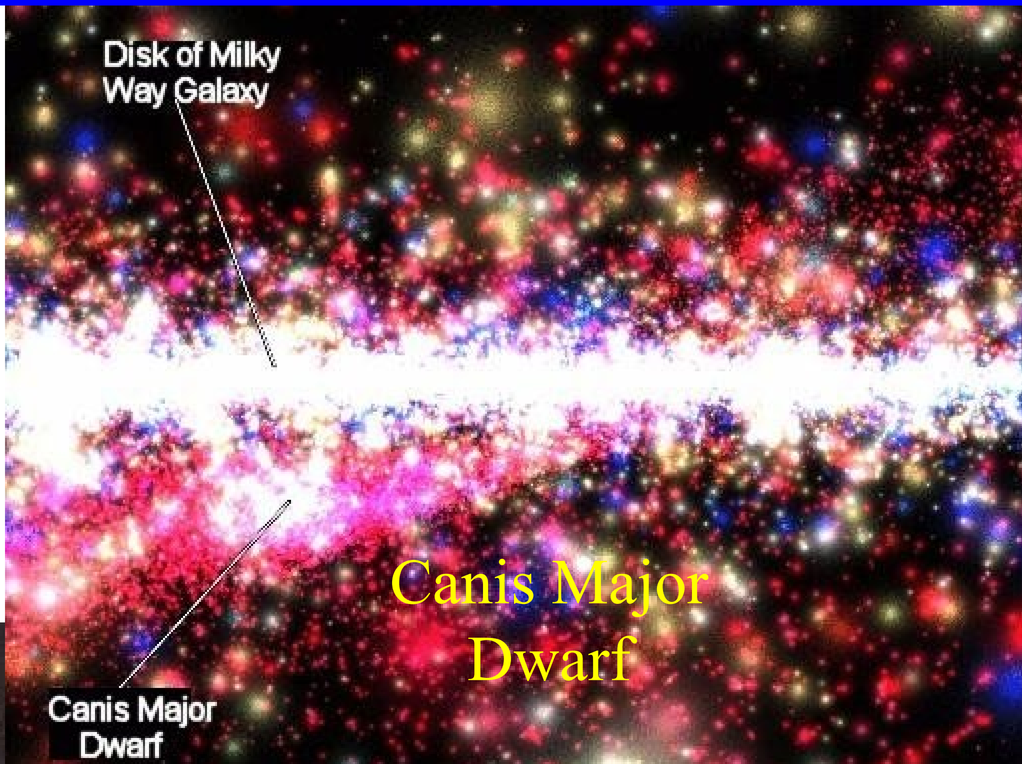
The Great Galaxy in Andromeda (M31)

- Large Spiral Galaxy - SAb
- About 50% brighter than our galaxy
- About 50% more mass than our galaxy
- 780 kpc away
- Moving towards us at 110 km/s
- Will merge with us in 4 Gy?

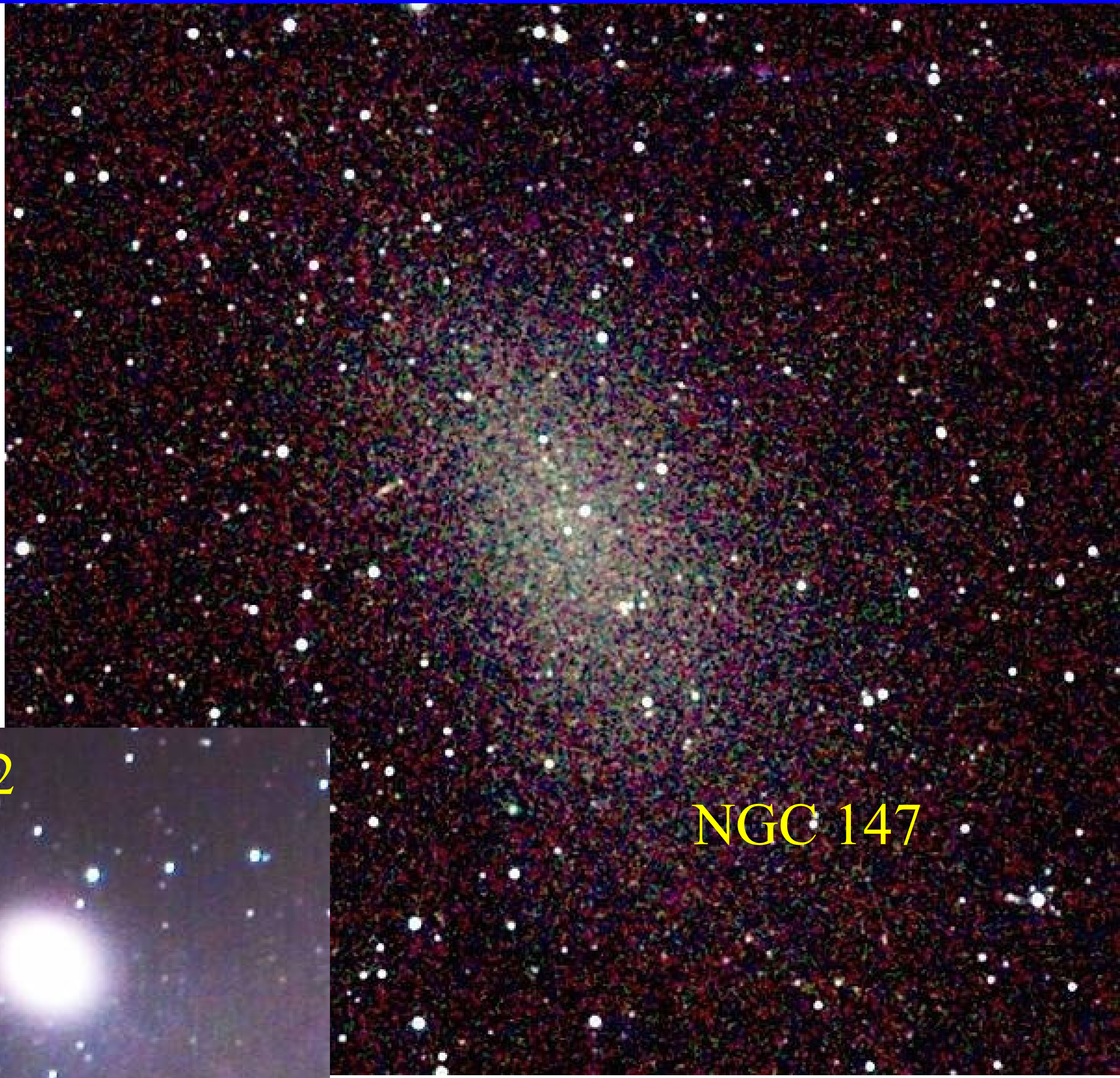
Our Companions (1)



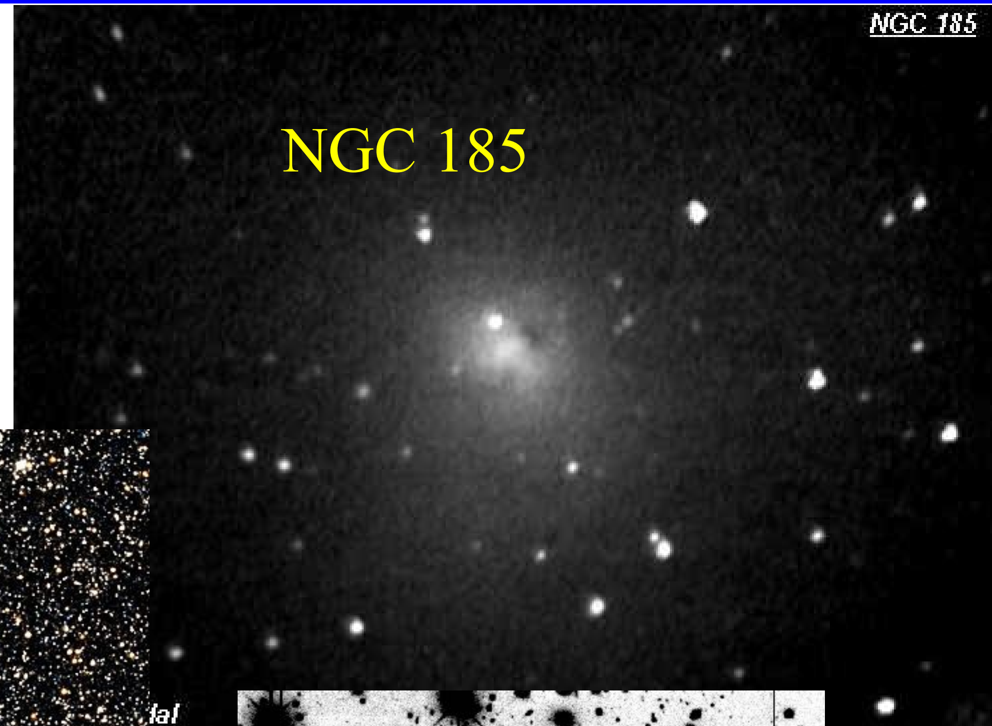
Our Companions (2)

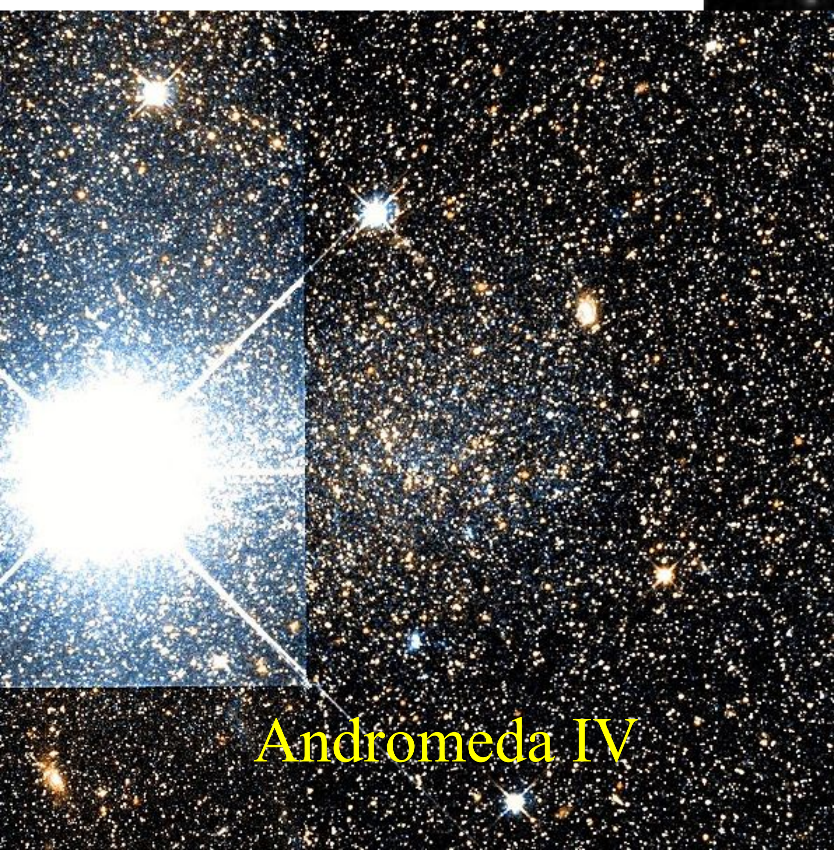


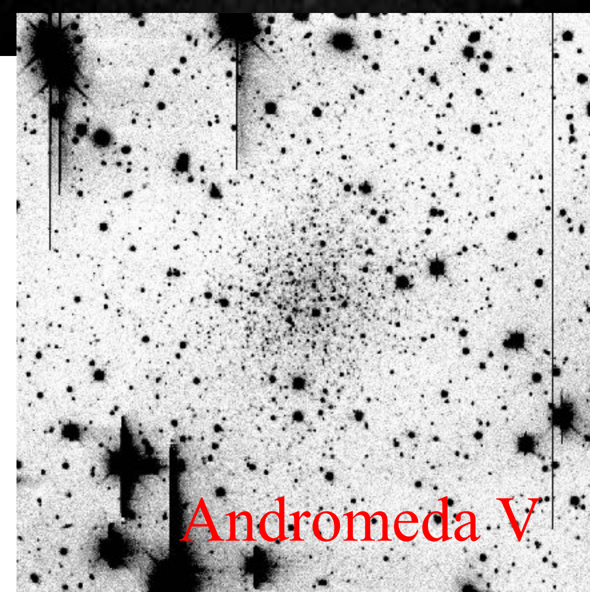
Companions of Andromeda (1)



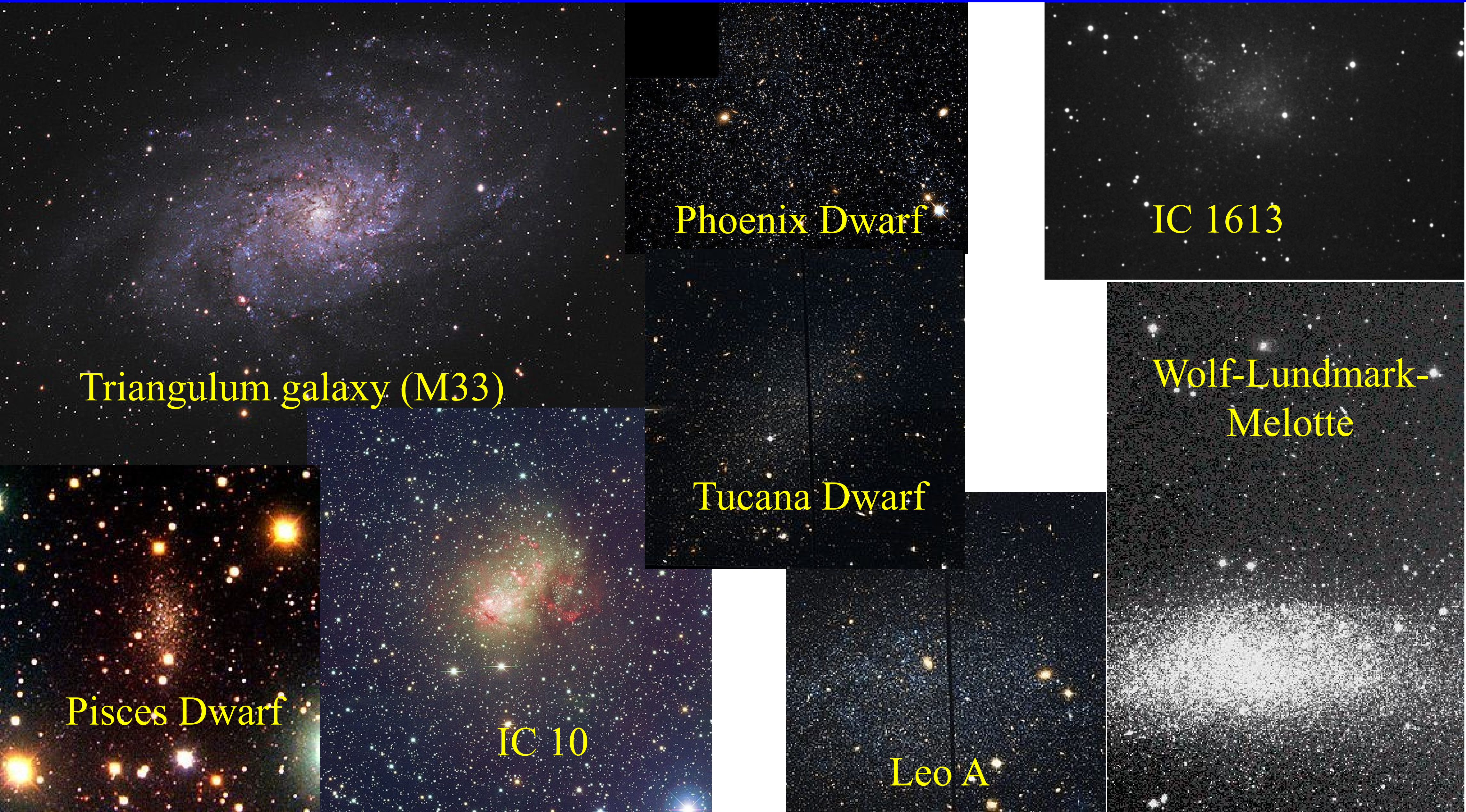
Companions of Andromeda (2)







Other Members of Local Group



Nearby Groups and Clusters

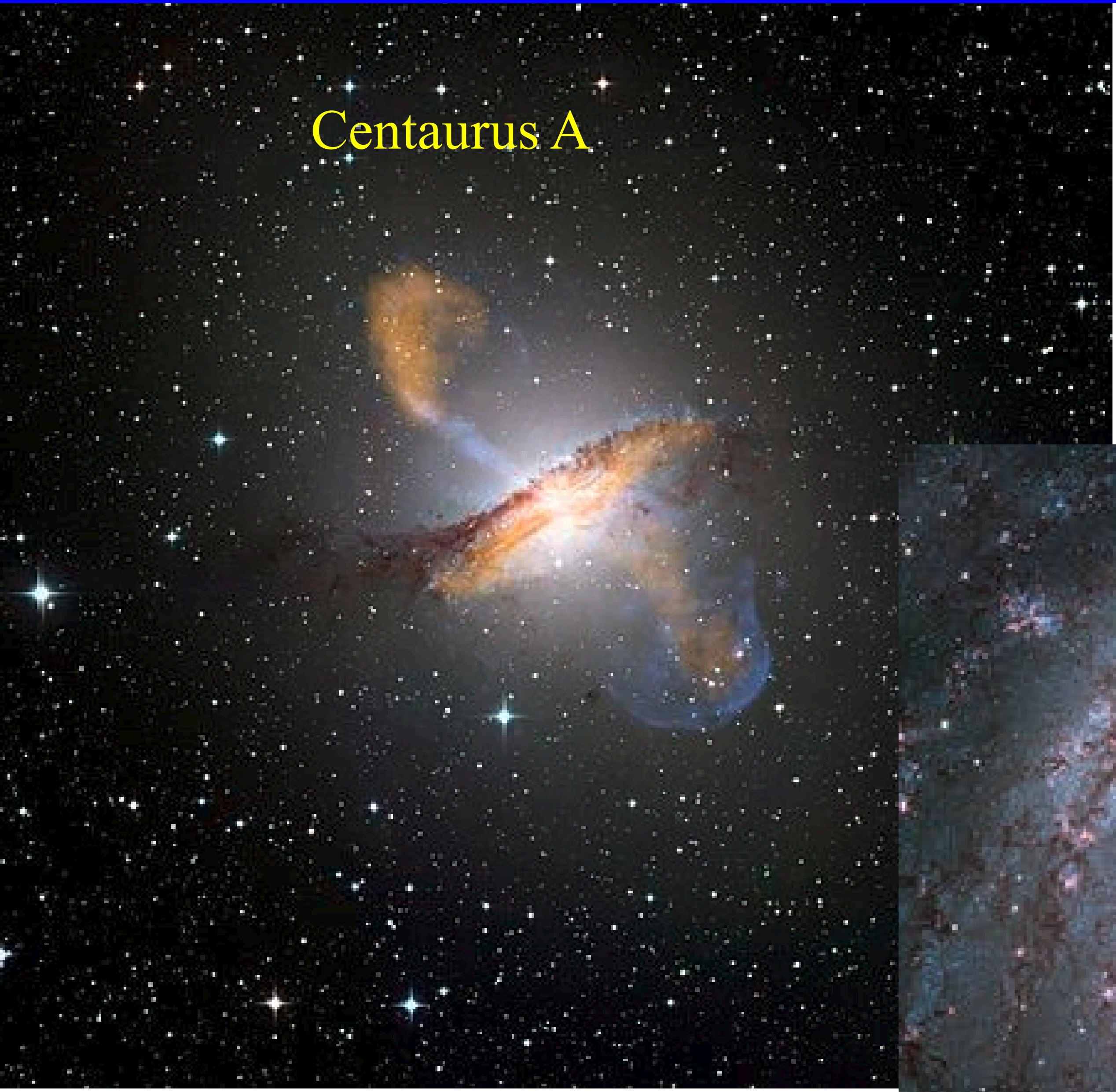
Maffei/IC 342 Group

3.3 Mpc

M81 Group

3.5 Mpc

Centaurus A / M83 Group



3.66 Mpc

Sculptor Group

3.9 Mpc

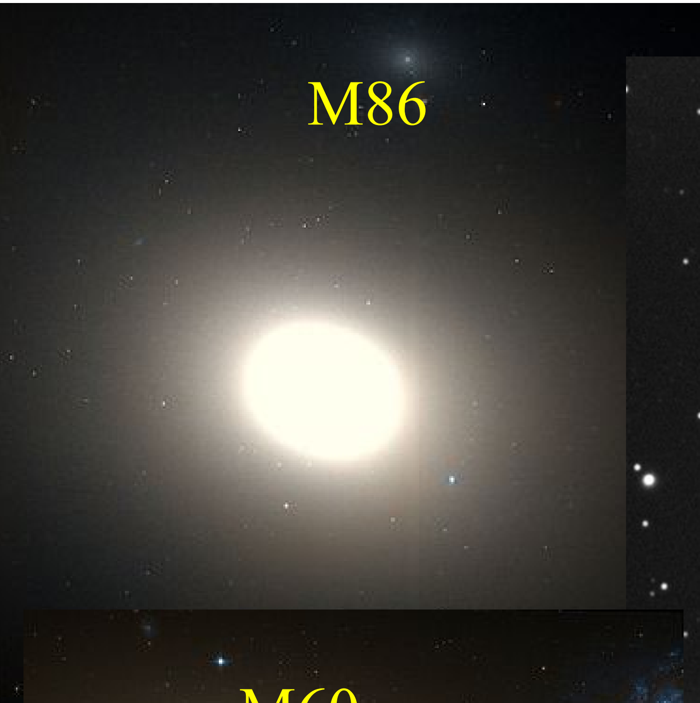
Venatici I Group

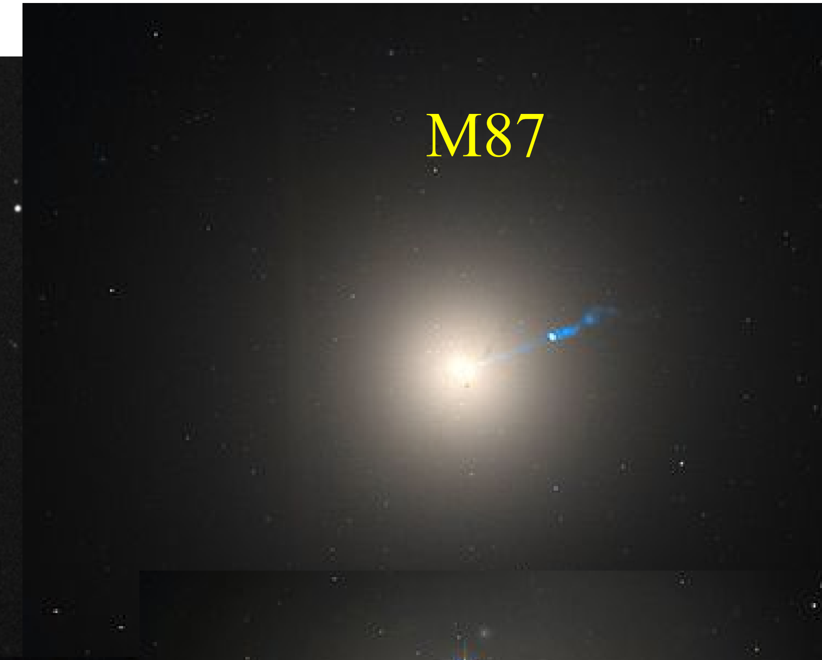
4.0
Mpc

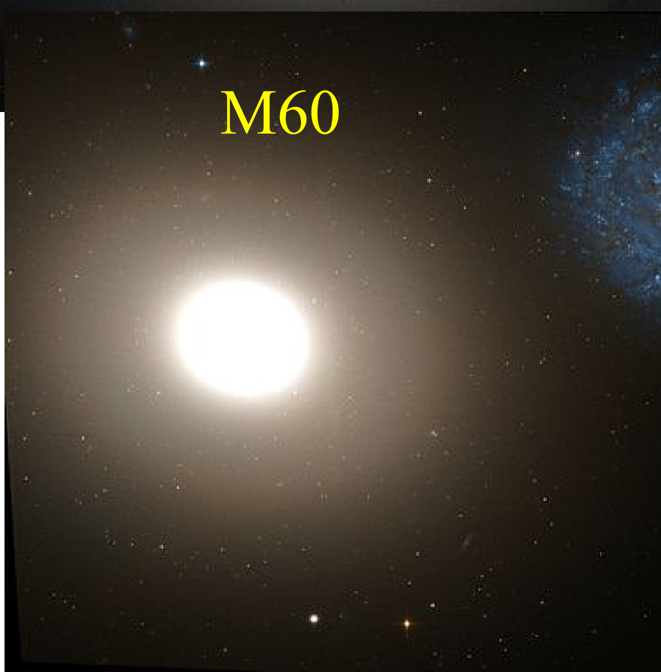
The Virgo Cluster

- More than 1000 galaxies
- Dozens of bright galaxies
  - Two giant ellipticals
  - Many bright spirals
- 16.5 Mpc away
- Total mass about $1.2 \times 10^{15}\ M_{Sun}$

Some Members of Virgo

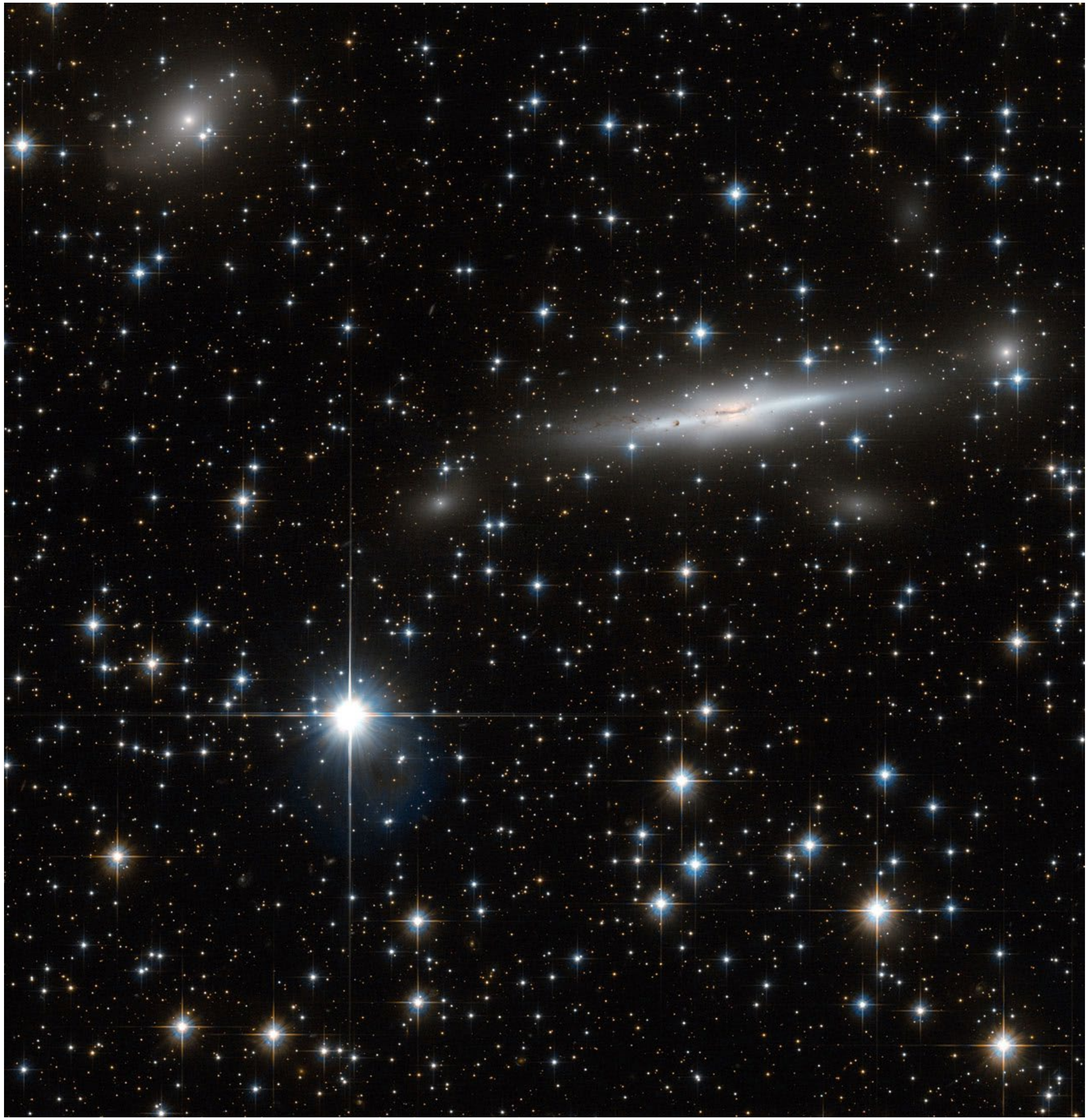




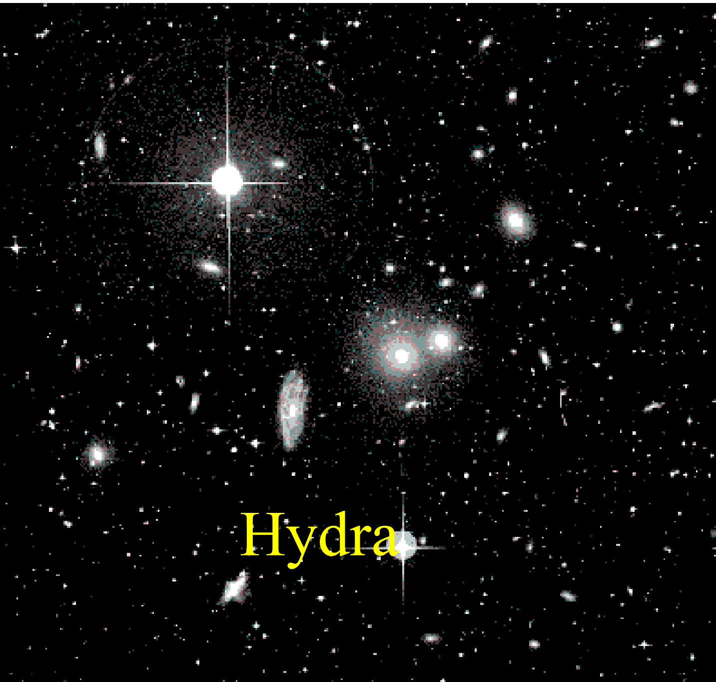


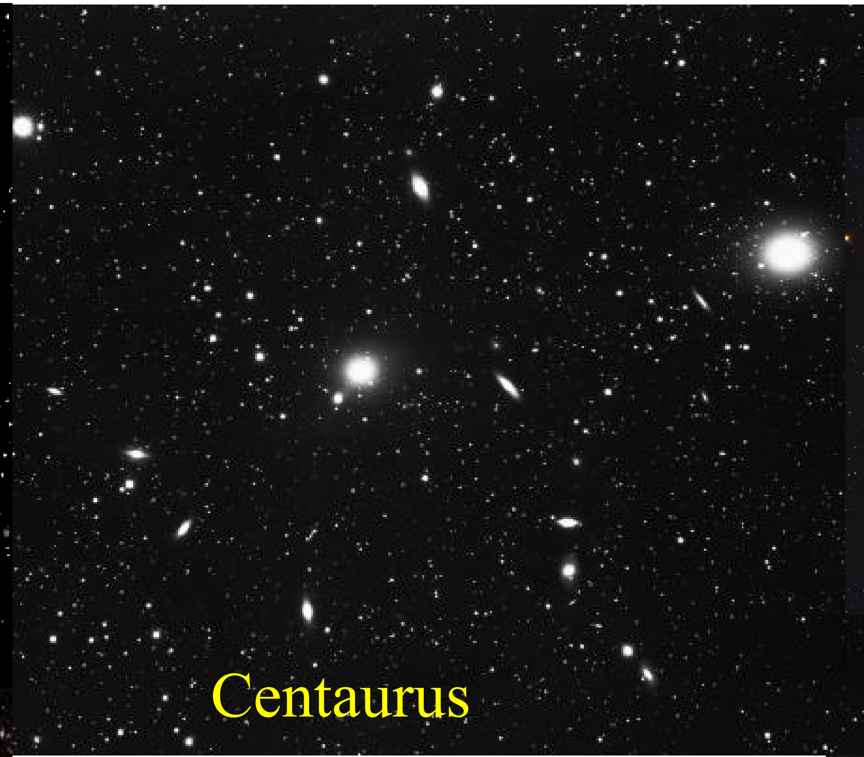
The Norma Cluster

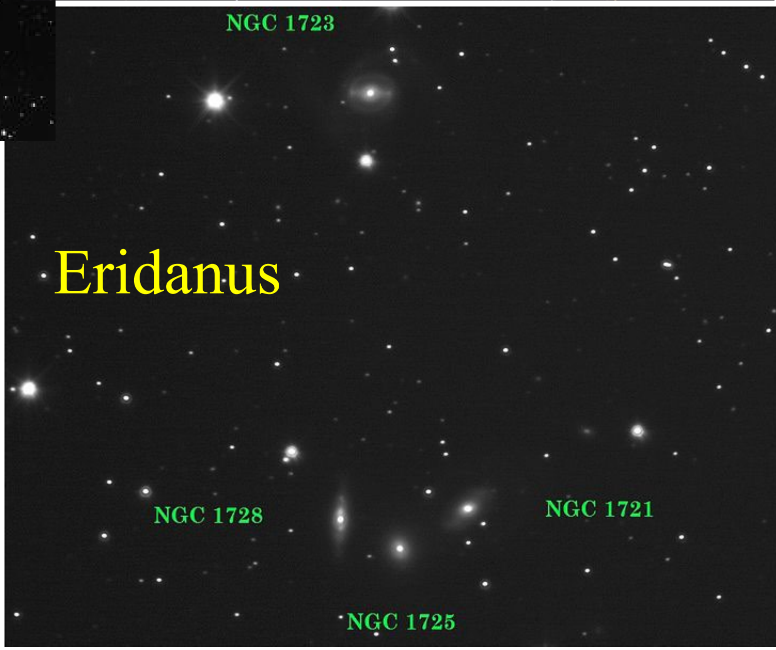
- Difficult to study because our galaxy in the way
- About 68 Mpc away
- Total mass > 10^{15} M_{sun}
- Near the center of our supercluster



Other Clusters In Our Supercluster

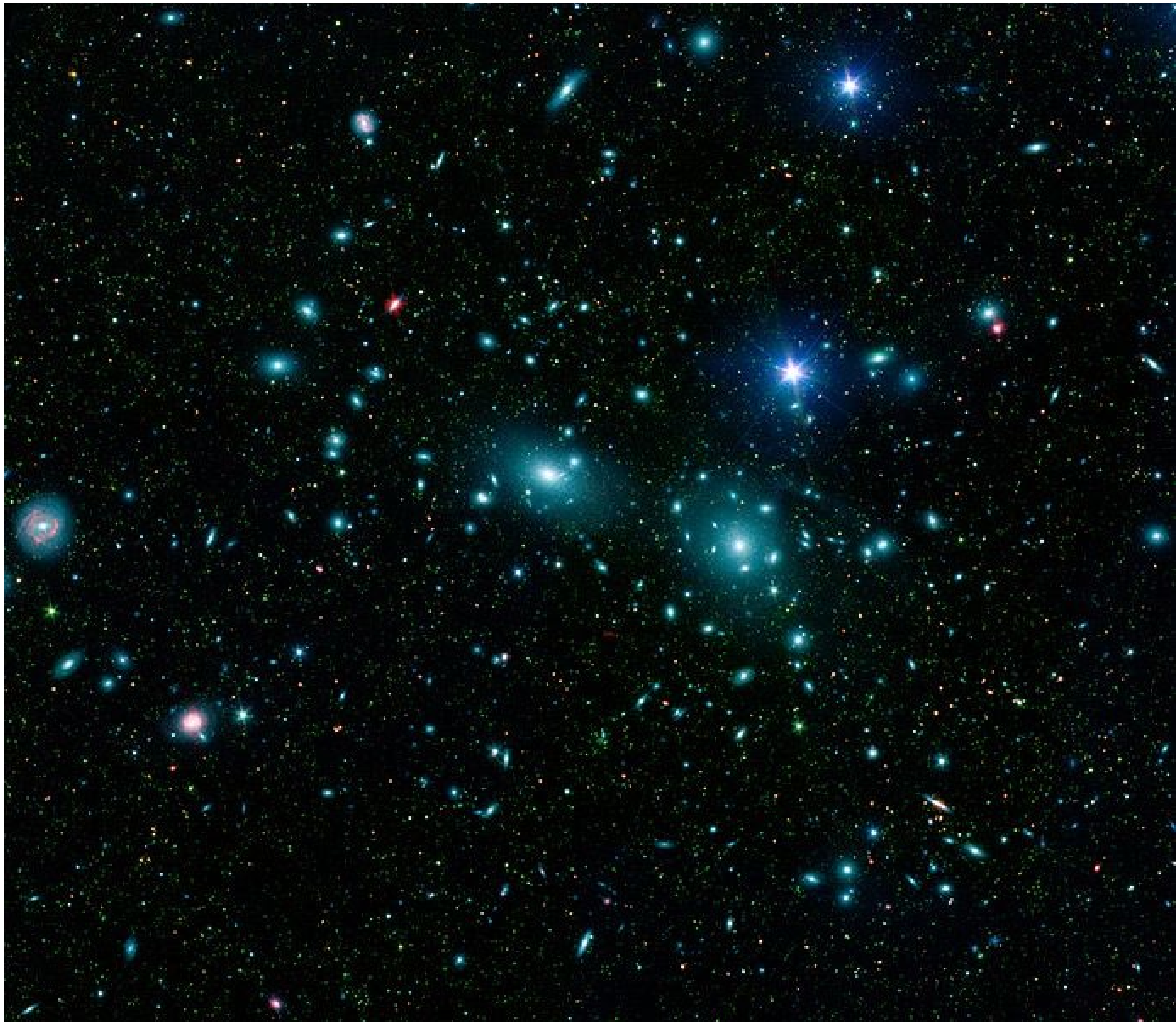






The Coma Cluster

- 1000+ galaxies visible
- Many bright galaxies
  - Many giant ellipticals, especially in the center
  - Bright spirals towards the edges
- About 99 Mpc away
- Total mass about $3 \times 10^{15}\ M_{\mathrm{sun}}$
- Center of Coma Supercluster



Groups/Clusters and the Virial Theorem

- The dynamical time is how long it takes for a galaxy to go through one cycle of orbiting the cluster

- For groups, like the Local Group, this time scale can be very long
  - Probably of the order of 15 Gyr or more for the Local Group
  - Probably the upcoming Milky Way/Andromeda encounter will be the first such encounter

- For clusters, they have more mass, so everything goes faster
  - Galaxies, especially near the center, will have orbited one or more times

- In one dynamical time period, the system will *virialize*
  - Satisfy the virial theorem
  - Will start to get more spherical in shape

- Typically, the galaxies near the center will virialize first

$$2E_K + E_P = 0$$

- Outer galaxies will take longer

Cluster and Group Evolution

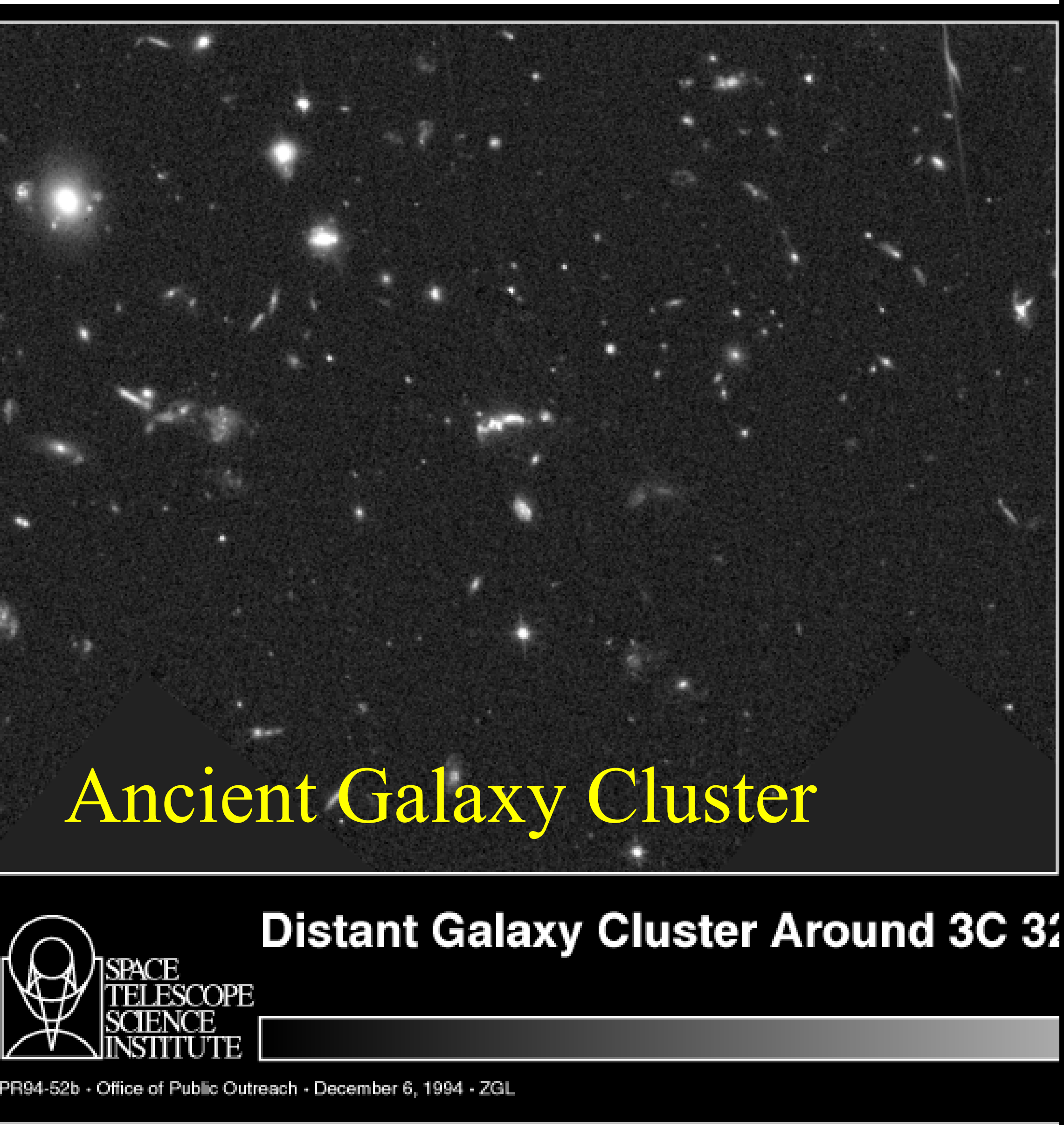
Galaxy Clusters and Groups change over time:

- Heaviest galaxies fall towards the center
- Tidal friction will enhance this effect
- Galaxies will merge

For clusters, over time:

- System will form a spherical distribution (more regular)
- In the center, galaxies will coalesce
  - Giant ellipticals concentrated in the center
  - Spirals more towards the edge.
- Collisions will knock gas out of the galaxies themselves
  - Twice as much gas *between* the galaxies as *in* the galaxies

Old Clusters



Is There Gas Between the Galaxies?

- Collisions between galaxies have knocked much of the gas completely out of the cluster

- Hot gas produces X-rays
- *In principle*, it is possible to measure total amount of gas between galaxies by measuring the quantities of X-rays
- *In practice* this is very difficult because the gas may be non-uniform in temperature, density, composition …
- Rough estimate: there is twice as much gas between that galaxies as in the galaxies
- However, there also could be dark matter between the galaxies
- We would like a way to estimate the total mass of the entire cluster

Mass of the Cluster from Virial Theorem

- If the galaxies have time to virialize, we can get an idea of the mass of the cluster
- The kinetic energy is proportional to the velocity squared

$$2E_K + E_P = 0$$

- The potential energy is proportional to the total mass of the cluster
- Problem: not all galaxies will have had a chance to virialize
  – Introduces a bias into the measurement
  – Solution: use the elliptical and lenticular galaxies
- But this is not a foolproof way to make sure they are virialized
- Bottom line: This is a difficult way to get an accurate number

Mass of the Cluster from X-rays

- Hot gas has been knocked out of the galaxies
- Pressure wants it to leave
- Gravity wants it to stay
- If it isn't leaving, then the two must balance
- By studying temperature, we can estimate pressure
- Assuming it is in balance, we can estimate mass

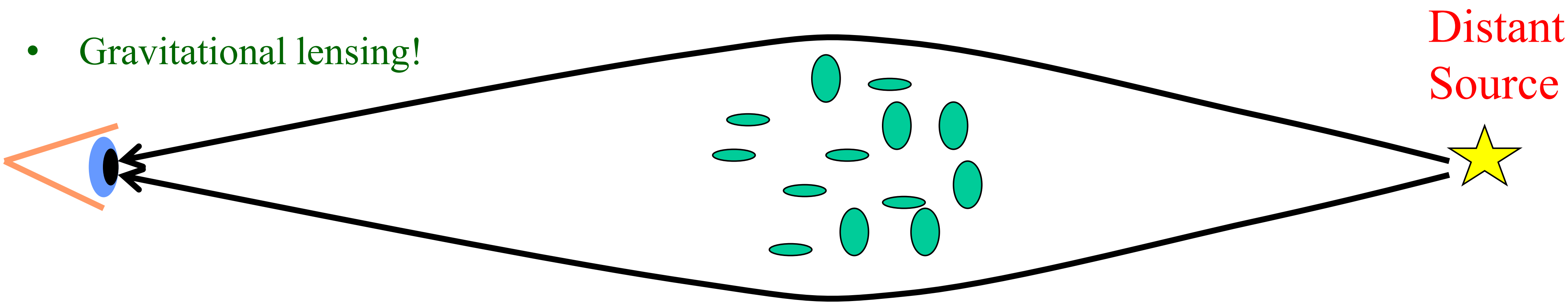
- Problem: Gas might have several components at different temperatures
- Problem: Gas might not be in equilibrium – it could be leaving
- Bottom line: This is also difficult to do

Where is the Mass in a Galaxy Cluster?

- Most (all?) galaxies have much more mass than is in the stars and gas
  - Dark matter is 85% of galaxies' mass

- How about clusters?
  - Need to find mass of cluster

- Gravitational lensing!



- Gravity bends light

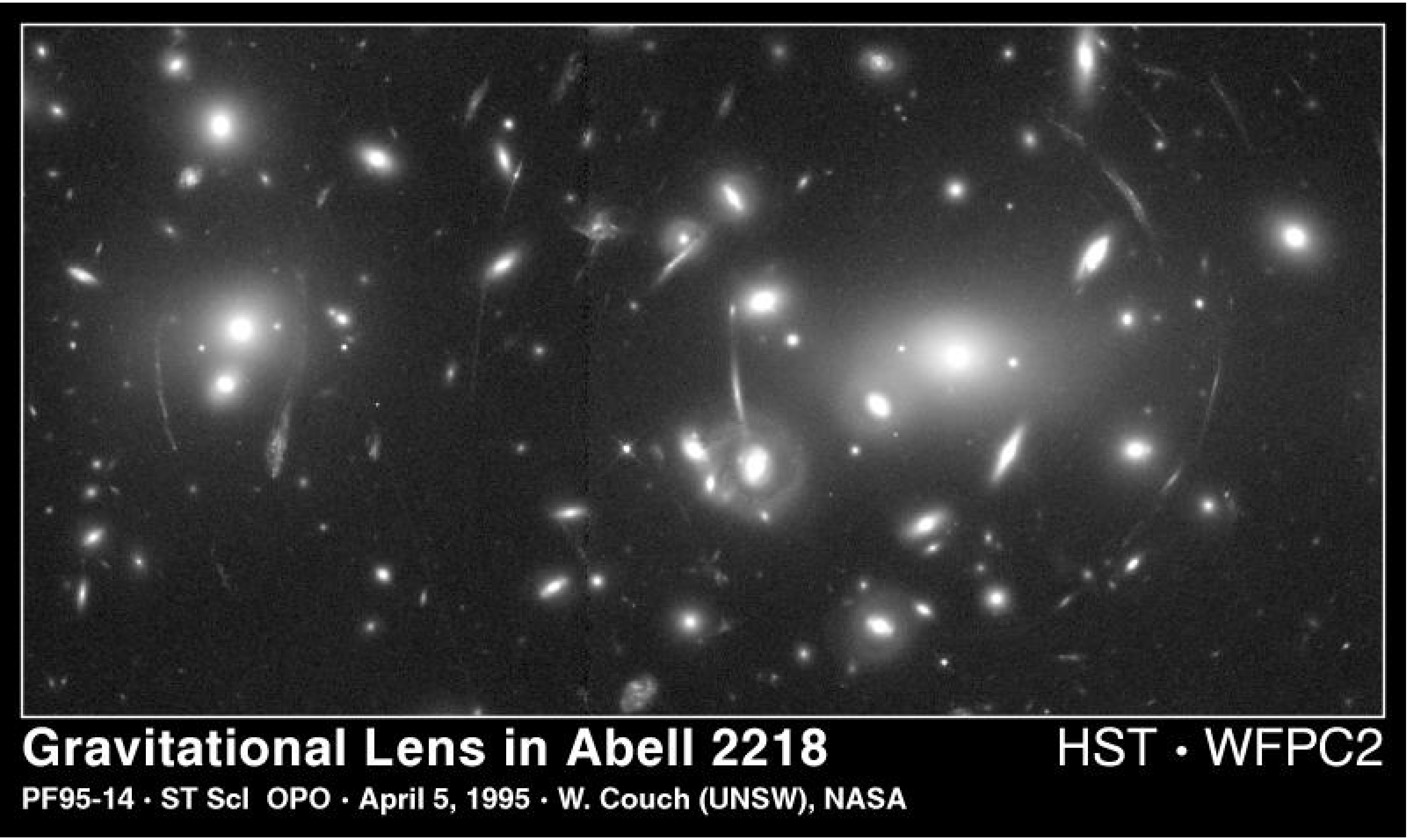
- You can see two or more images of source

- Can estimate mass of cluster!

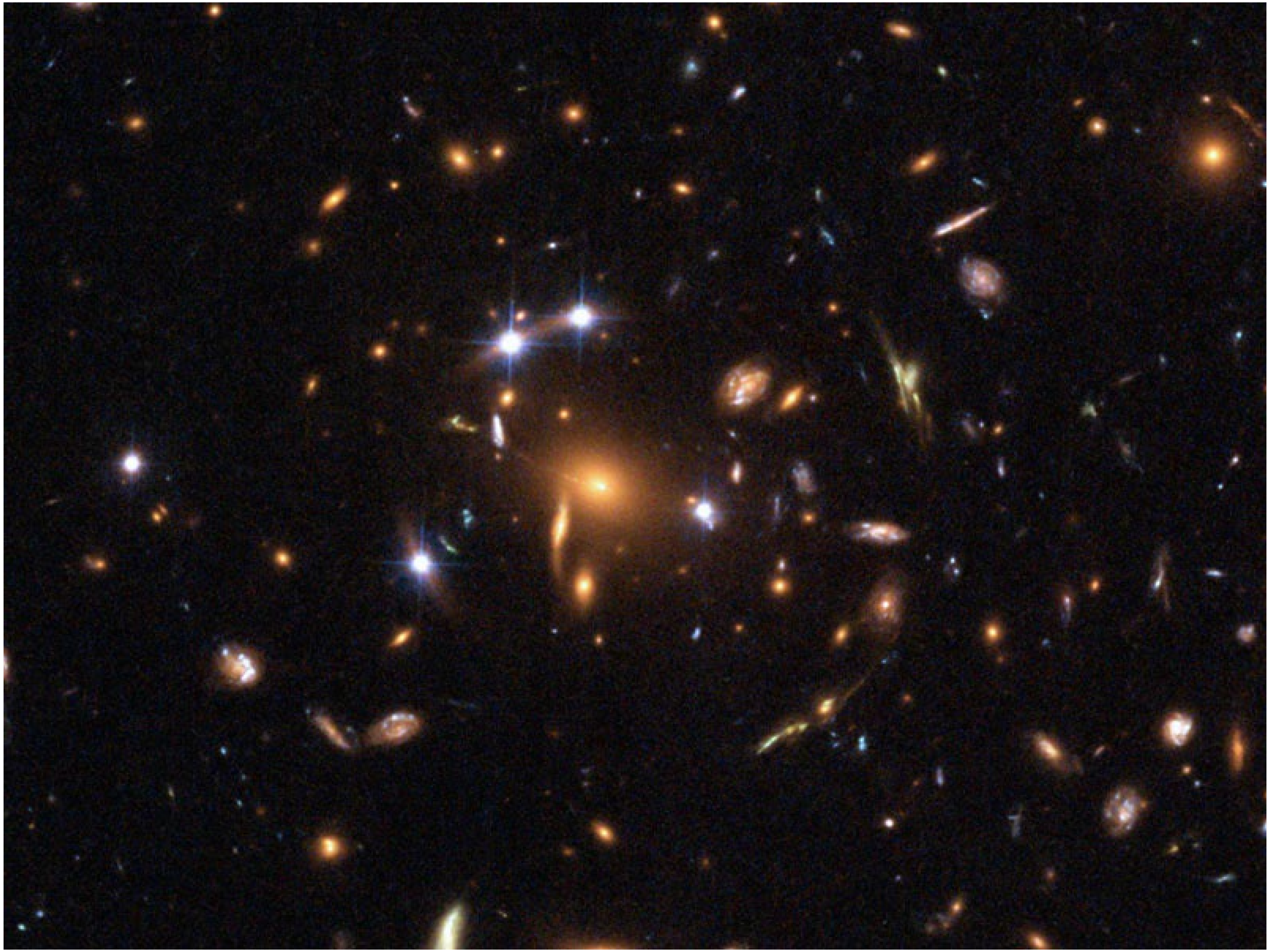
There's much more mass than is visible

- 5% is in stars and other visible matter
- 10% is in hot gas between the galaxies
- 85% is in dark matter

Clusters as Gravitational Lenses (1)



Clusters as Gravitational Lenses (2)

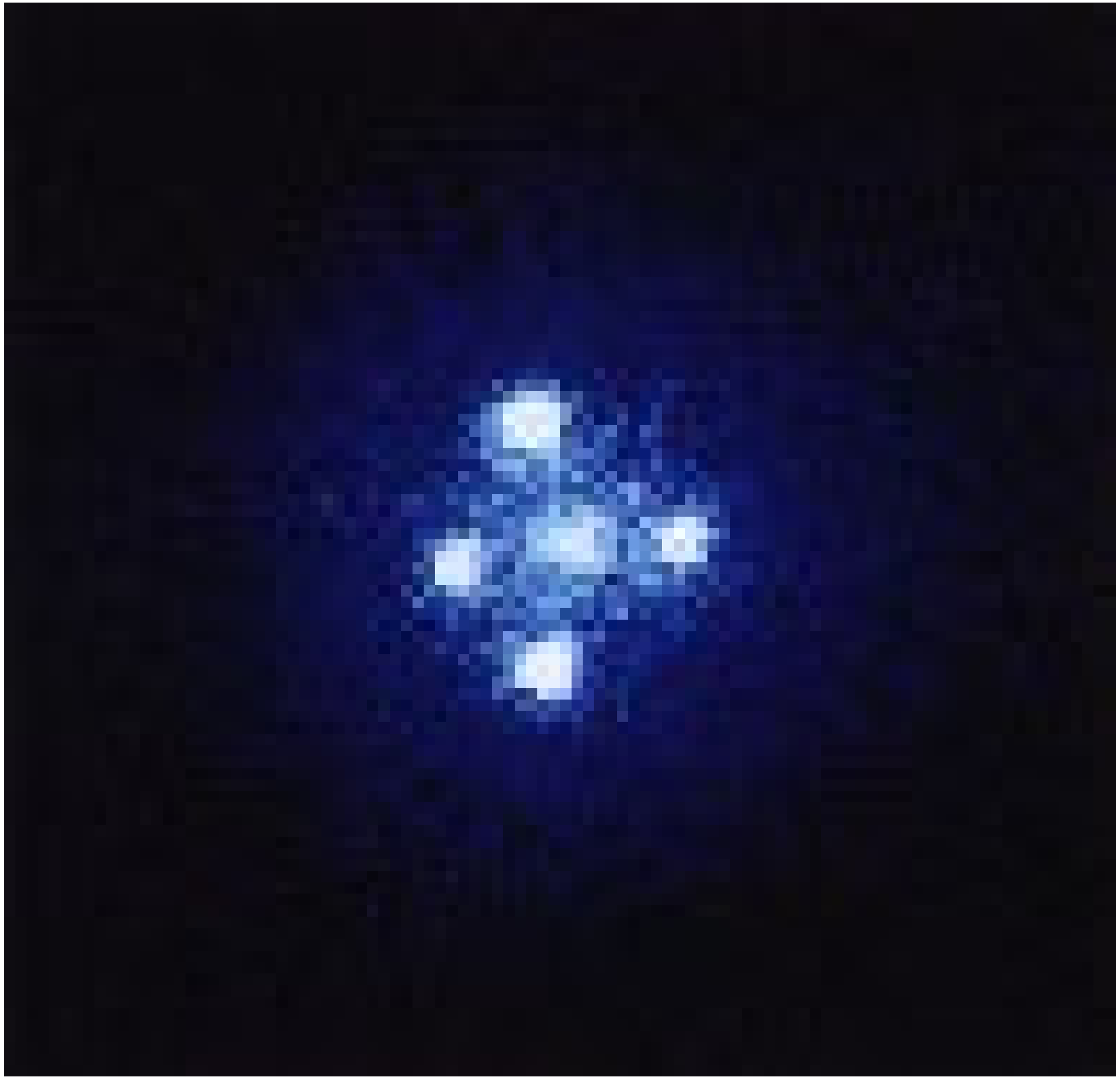


Clusters as Gravitational Lenses (3)

An Einstein Cross

- Can show lensing by a smooth object always produces an odd number of images

- In this famous example, a single object appears five times
  - Probably verified via its spectrum

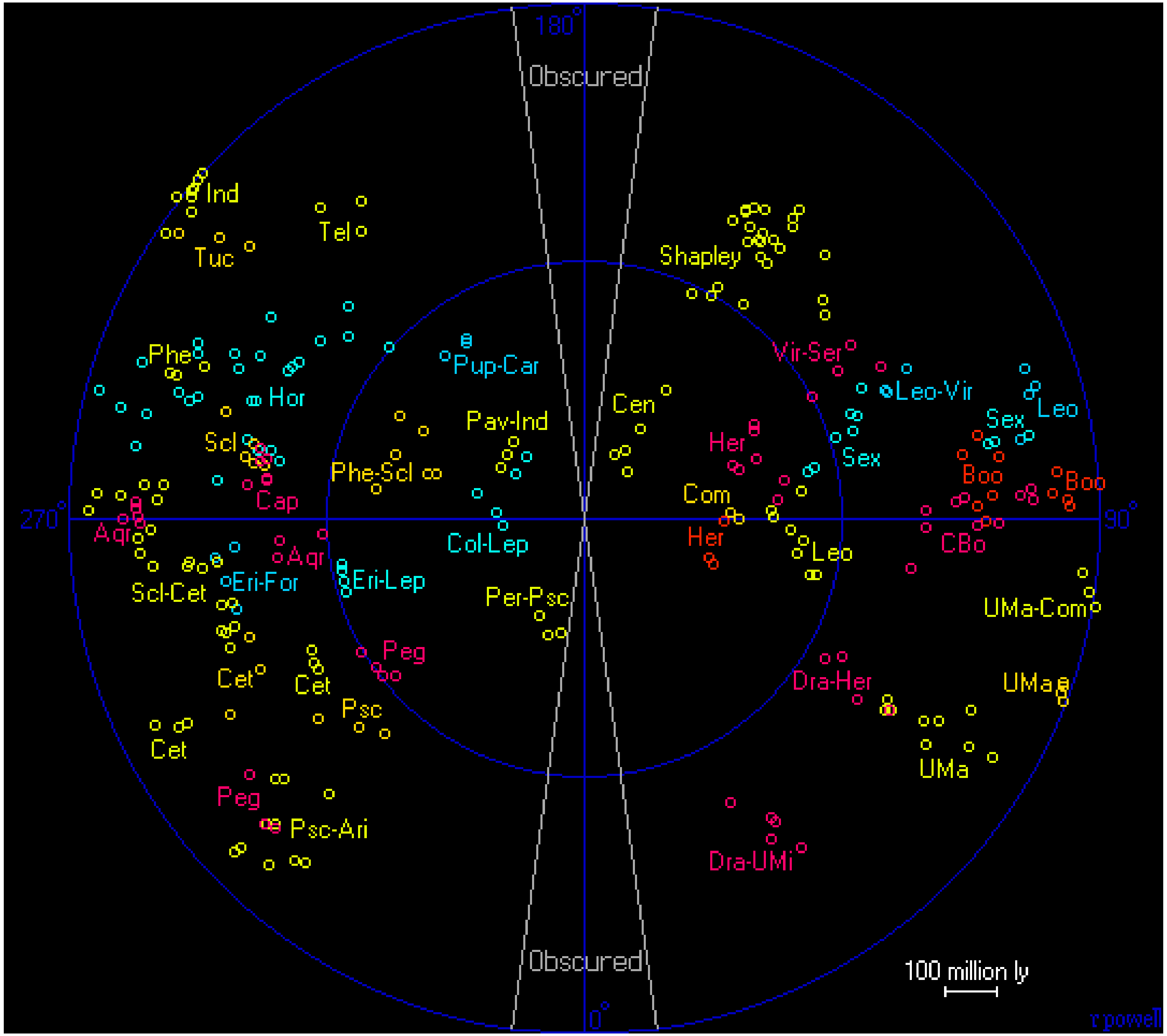


An Occasional Lucky Break

- We would like to see some of the most distant galaxies in the universe
- They are dim due to
  - Enormous distance
  - Red-shift
- Gravitational Lensing can magnify very distant objects, making them seem much brighter
- Although such luck is rare, there are so many clusters in the universe that it happens occasionally.

3D Map of Nearby Clusters

- Yellow are near the plane of the galaxy
- Blue are above the plane of the galaxy
- Red are below the plane of the galaxy



Superclusters

Where We Live

Levels of organization:

- Stellar Systems
- Stellar Clusters
- Galaxies
- Galaxy Groups and Clusters
- Galaxy Superclusters
- The Universe

Everyone should know where they live:

- The Solar System
- (we don't live in a cluster)
- The Milky Way Galaxy
- The Local Group
- Laniakea Supercluster
- The Universe

Groups/clusters are themselves grouped into larger structures called *Superclusters*

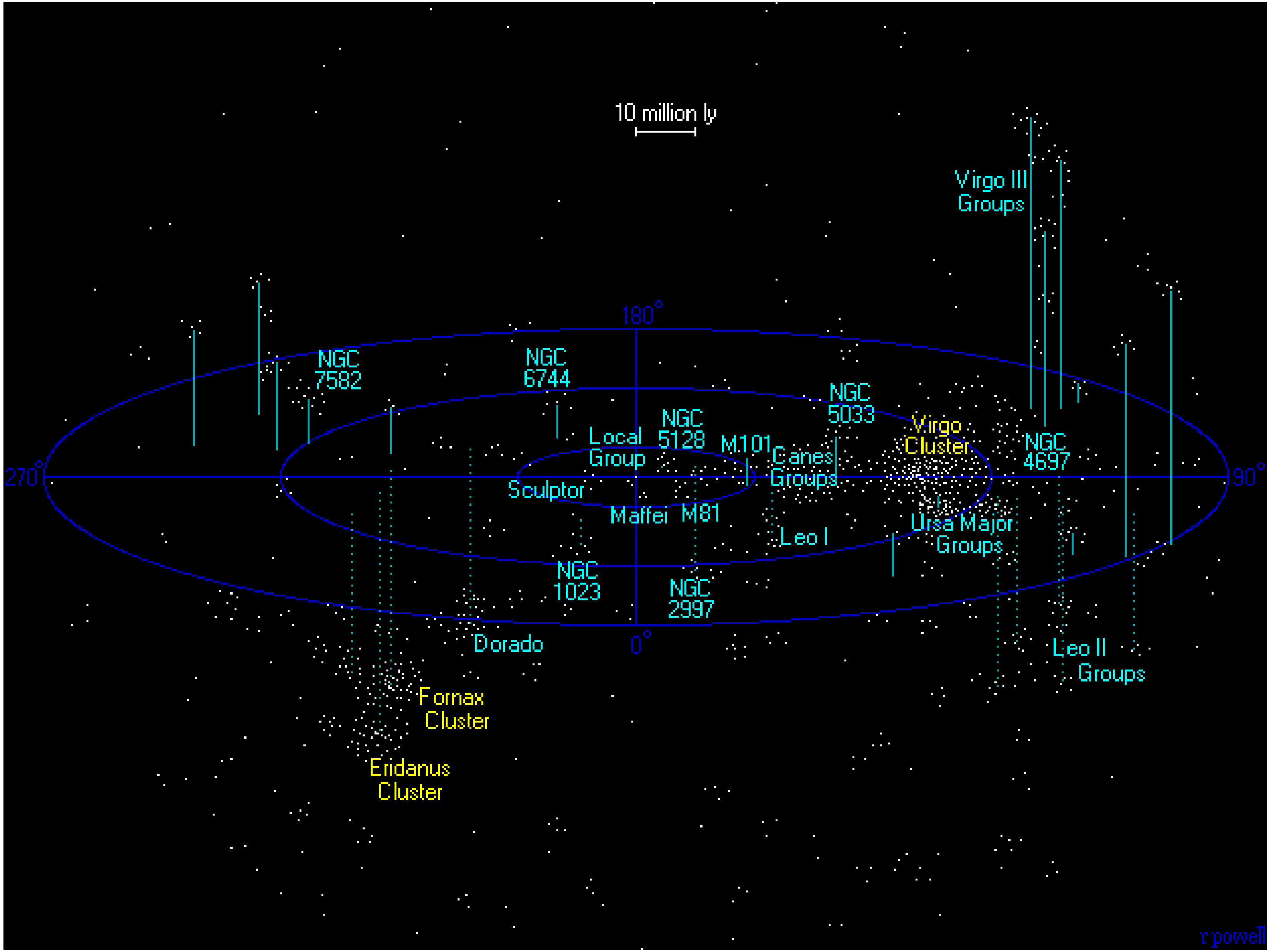
- Size: Up to around 200 Mpc
- Our supercluster is called the "Laniakea Supercluster"

- Superclusters are much more poorly defined than clusters

- At this scale, the universe hasn't had time to virialize
  - They are always irregular

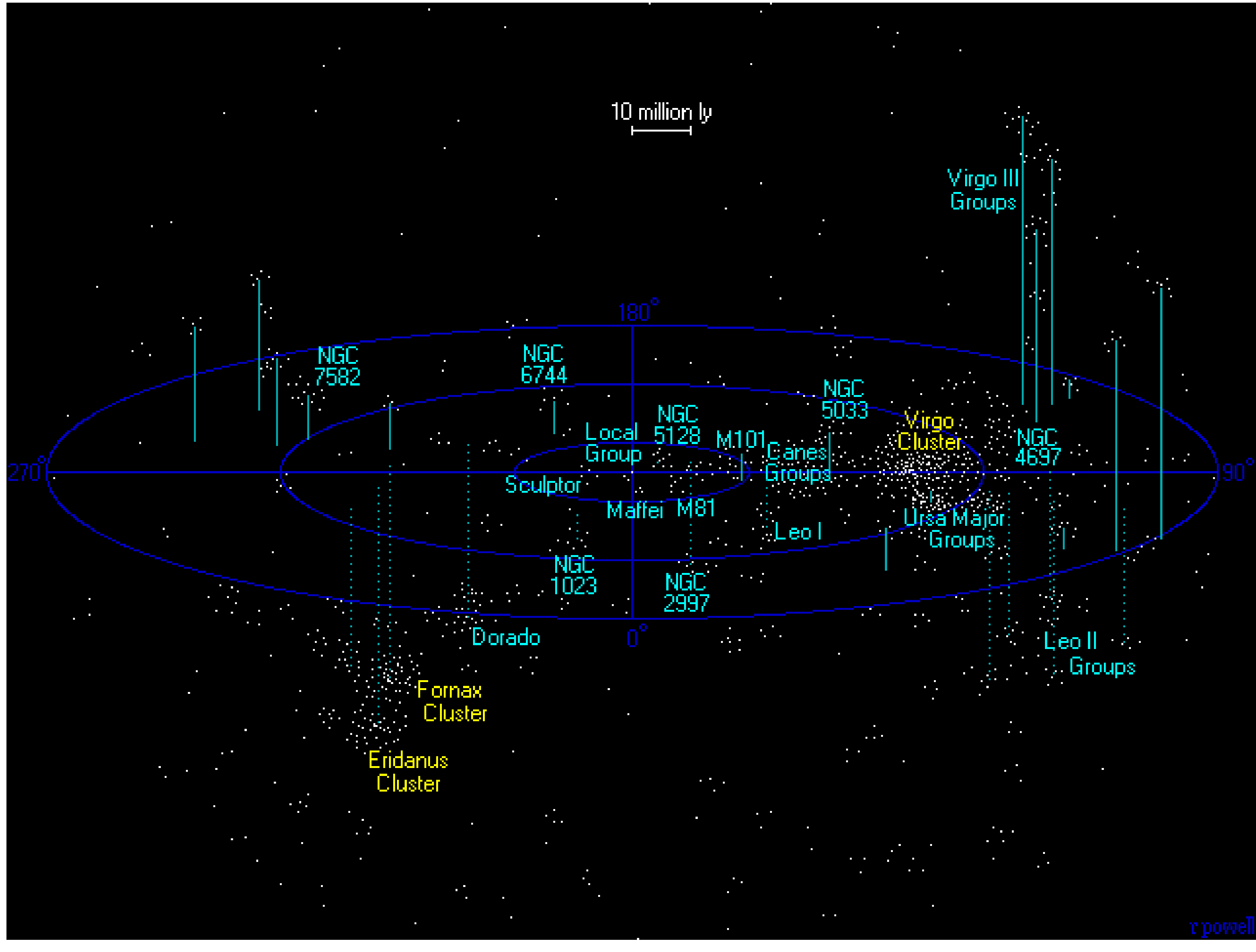
Virgo Supercluster

- Before 2014, it was known that the Local Group was part of a larger structure called the Virgo Supercluster
- More than 100 galaxy groups and clusters
- 33 Mpc across
- 7000 times the volume of the local group



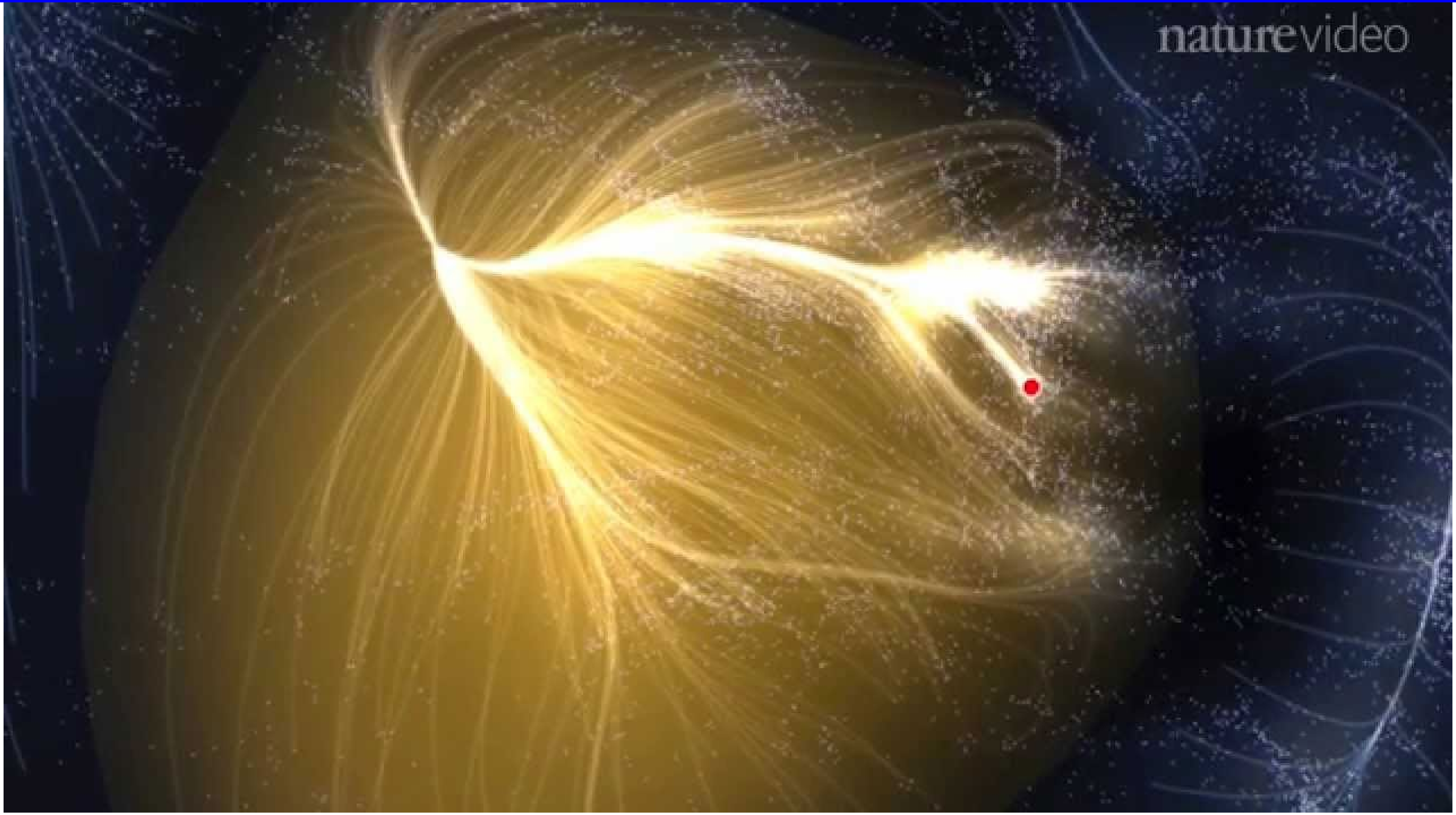
Virgo Supercluster?

- Virgo cluster is moving towards an object called the "Great Attractor"
- In 2014, a complete mapping of the motions of nearby clusters was performed
- It was realized Virgo is part of something larger



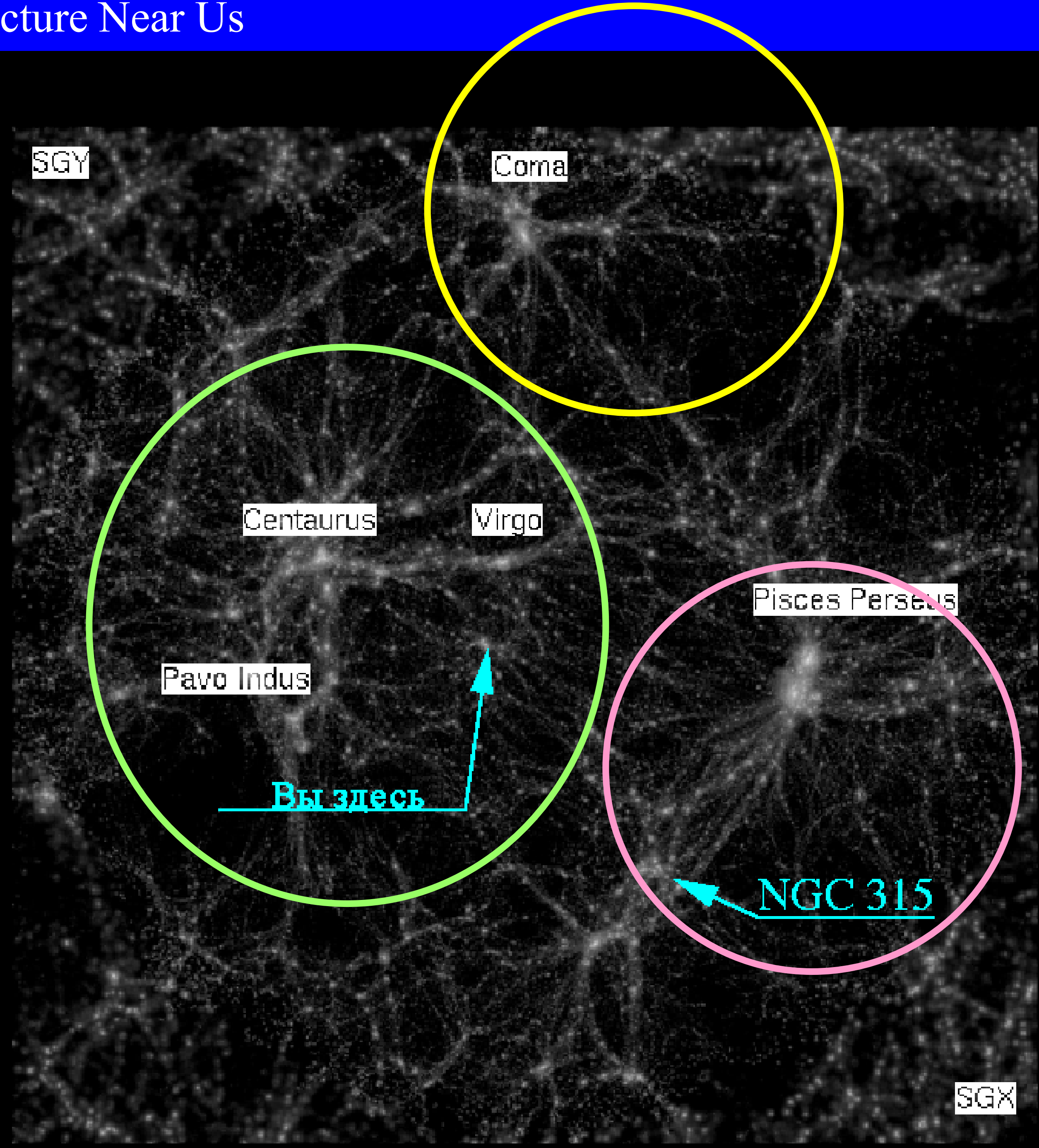
Laniakea Supercluster

- Discovered 2014
- Study of "flow" of nearby clusters
- Centered on Great Attractor, near Norma
- 160 Mpc across

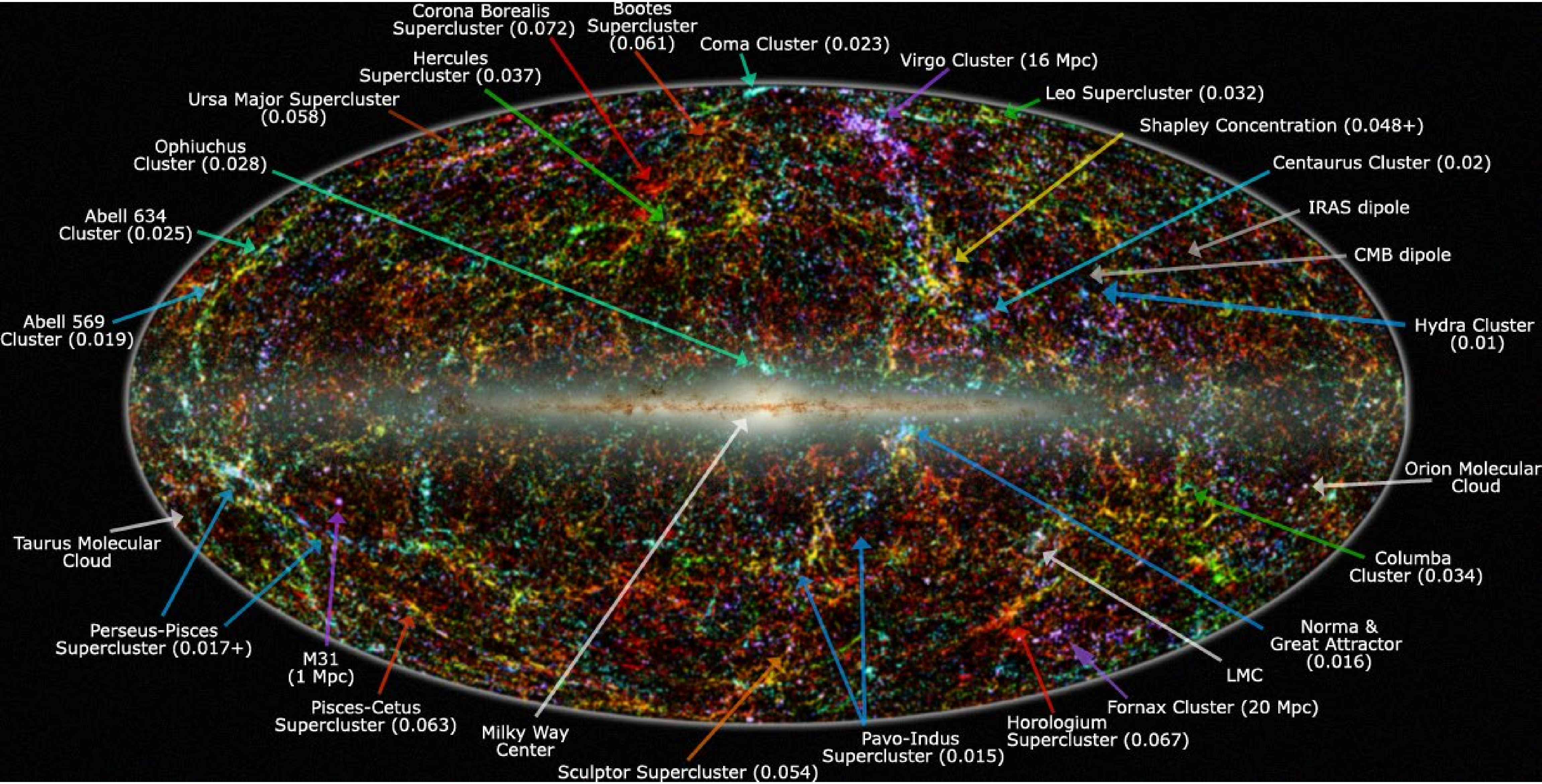


Structure Near Us

- Laniakea Supercluster
- Coma Supercluster
- Perseus-Pisces Supercluster



A Cool Picture I Found

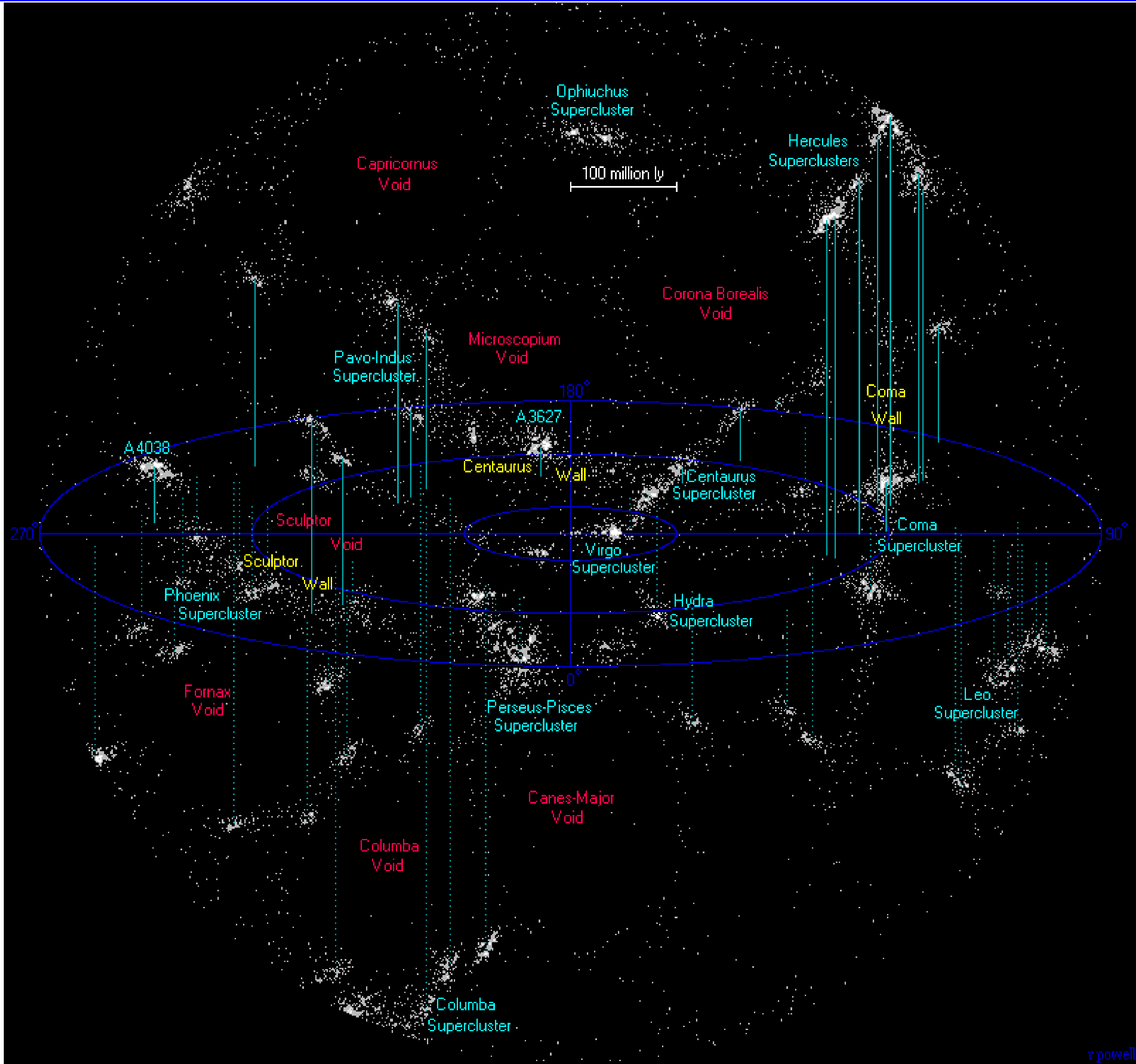


Nearby Superclusters

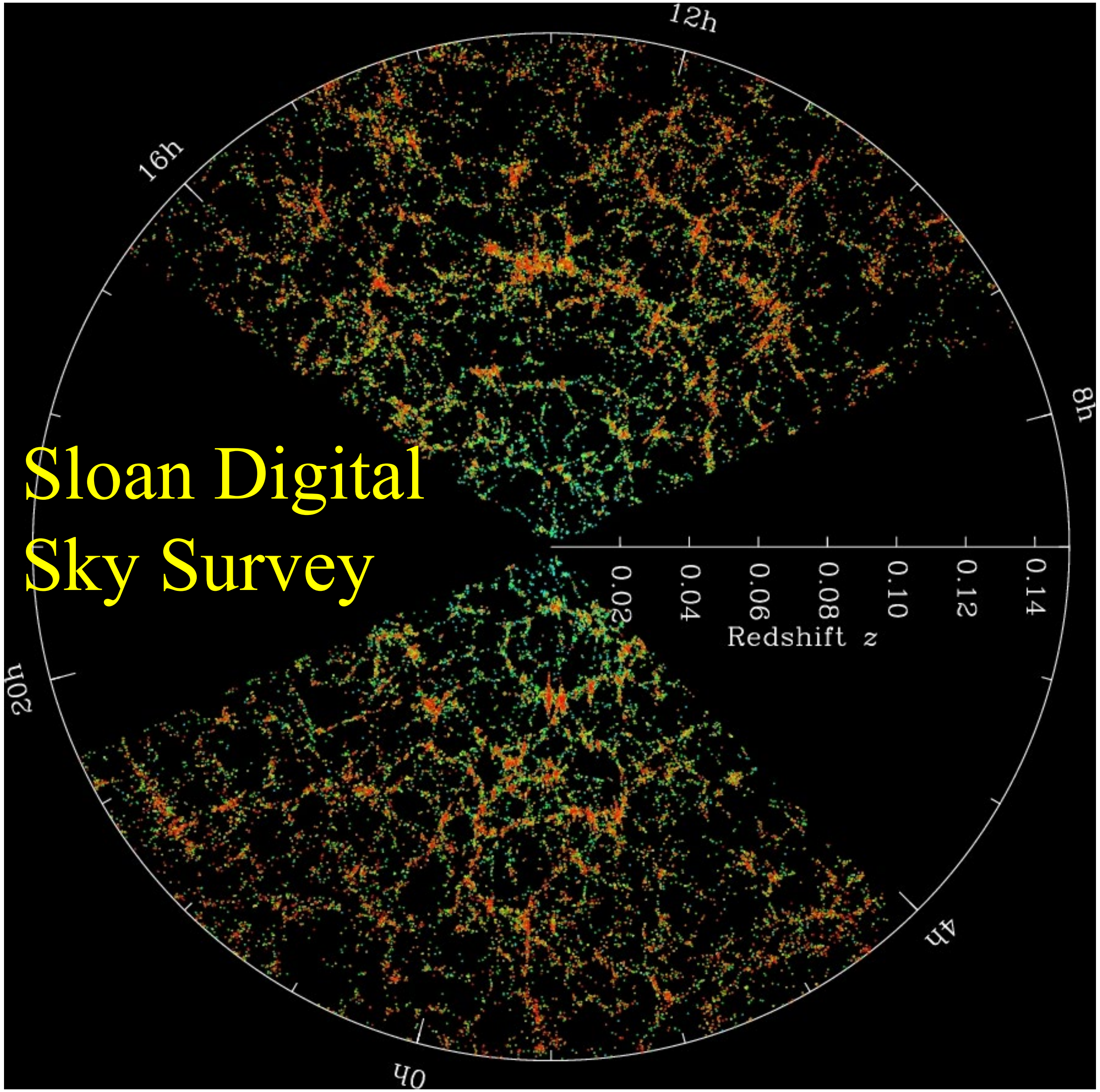
- Between the superclusters are "voids" almost devoid of galaxies

- Little evidence of structure bigger than superclusters
  - No "hyperclusters"

- Largest scale structure like soap bubbles
  - Mostly empty space
  - Superclusters are walls between the bubbles



Structure on the Largest Scale (1)



Structure on the Largest Scale (2)

- SDSS and similar projects have catalogued several millions of galaxies' distance
  - Actually it is recording red shifts. More on this later
  - Video
- Beyond nearby galaxies, they record the correlation function – the probability that galaxies are near each other
- Beyond 100 Mpc or so, this smooths out, indicating the universe is smooth
- It can be Fourier transformed – broken into waves – to see how much clumping there is at different wavelengths
- It falls off at very long wavelengths
  - With interesting additional features we will later discuss
- This behavior on very large scales helps us constrain how the universe formed the structure we see
- On scales larger than 200 Mpc or so, treat the universe as uniform